Diagnostics for the CEBAF FEL Injector**

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Abstract A test stand for the 10 MeV, 5 mA average current injector for the CEBAF FEL is currently under construction. The injector tests will progress through two phases. The first phase will be devoted to characterizing the gun transverse and longitudinal emittance performance as a function of bunch charge, beam size, and energy. The goal of the second phase is to achieve the nominal requirements of the 10 MeV injector, including bunch length, emittance, charge per bunch, and energy stability. This paper summarizes the diagnostics planned to be used in these experiments.

INTRODUCTION

A 10 MeV, 135 pC/bunch, 5 mA average current injector for the proposed 1 kW average power CEBAF UV FEL has been designed (1,2,3) and a test stand is under construction. Two main goals of the test stand studies are to establish the nominal injector operating conditions for the FEL and to characterize the injector to an extent that it can be accurately modeled using the numerical code PARMELA. The beam diagnostics are critical to attaining these goals. Since many of the diagnostics used in the 10 MeV injector will also be used in the main FEL accelerator, these tests also offer the opportunity to verify the proper operation of diagnostic systems.

The measurements will fall into two phases. The first set of measurements will be performed on the 500 keV photocathode gun. Measurements will include transverse and longitudinal emittance as a function of energy, transverse focusing, bunch charge, and transverse and longitudinal laser spot profiles. When these are completed, the 10 MeV beamline will be installed and measurements of energy, energy spread, energy stability, transverse emittance, bunch length, and energy-phase tilt will be performed.

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500 KEV GUN TEST STAND

When the 10 MeV beamline is fully installed, the 500 keV beamline will have minimal diagnostics, specifically, 1 fluorescent viewer, 1 BPM and 1 wire scanner. Therefore it is critical to characterize the gun and develop an accurate model for simulation. This characterization will involve observing the effect on transverse and longitudinal emittances as energy, transverse focusing, bunch charge, and transverse and longitudinal laser spot profiles are varied. Since later setup and troubleshooting of the 500 keV region will rely heavily on modeling, PARMELA simulations will be compared with experimental data with the goal of developing a reliable numerical model.

A schematic of the 500 keV test stand is shown in Figure 1. The 500 kV DC gun (4) uses a GaAs photocathode as its source. The 5 W photocathode drive laser pulse enters the light box perpendicular to the beam line, strikes a mirror and is reflected to the GaAs cathode. The location and size of the laser spot on the cathode will be measured using another light box mirror and a camera. The generated electron beam passes from the gun through a solenoid and the light box. Next, a 1 mm diameter round aperture and kicker cavity are located downstream of the light box, which will be in place only for the longitudinal emittance measurements. A movable slit, to be used for transverse emittance measurements, is located after the kicker cavity. A spectrometer magnet will either steer the beam into the spectrometer leg for energy and energy spread measurements or into a straight line for transverse emittance or bunch length measurements. A fluorescent viewer and wire scanner will be located on both the straight section and the spectrometer leg. Finally, the beam will be dumped into a water cooled

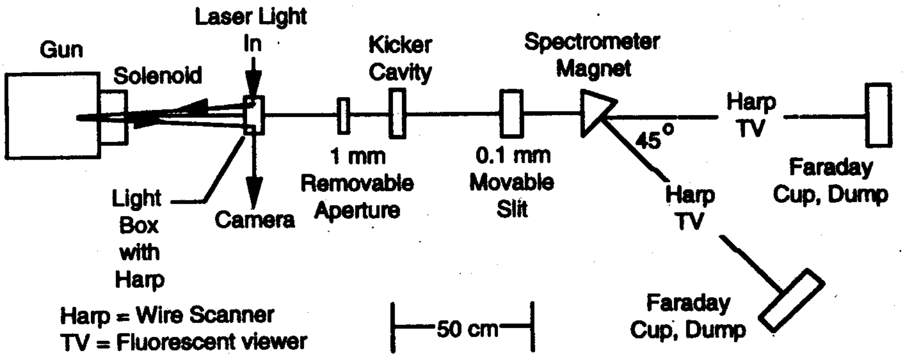


FIGURE 1. The layout of the 500 keV gun test stand showing locations of components and diagnostics.

re-entrant dump, electrically isolated to serve as a Faraday cup. The nominal values for beam parameters and the corresponding diagnostics are listed in Table 1. Specifics of the individual diagnostics are discussed below.

TABLE 1. Summary of 500 keV Beam Parameters and Associated Diagnostics

Parameter	Nominal value	Range	Technique	Anticipated Resolution
Position	0 mm	±5 mm	Fluorescent viewers	±0.25 mm
Profile	3 mm, rms	1-5 mm, rms	wire scanners	25 μm
Energy	500 keV	200-500 keV	Spectrometer / viewer	5 keV
Energy spread	6 keV	0.2 - 25 keV	Spectrometer magnet, wire scanner	0.5 keV
Bunch charge	135 pC	1 pC - 1 nC	Faraday Cup	1%
Transverse emittance	5π mm-mrad, rms, norm.	0.2-20π mm-mrad, rms, norm.	Slit/wire scanner	20%
Bunch length	35 psec (4σ)	10 - 60 psec	1497 MHz kicker cavity	<5 psec
Long. emittance	7 keV-degrees	5-25 keV degrees	kicker cavity/ spectrometer	±2 keV-degrees

Beam Position, Profile, Energy, Energy Spread, and Current

Beam threading will be accomplished, with some difficulty, using fluorescent screens viewed by CID cameras. I/V amplifiers on both the 1 mm aperture and the slit will be used to detect beam at those locations. The beam profile emerging from the gun will be measured using a 50 μm tungsten rhenium wire scanner in the light box. Energy and energy spread will be measured using the spectrometer magnet, the viewer, and wire scanner. Beam current will be measured using the Faraday cup at the beam dump. The charge per bunch will be calculated using the beam current data.

Transverse Emittance

The beam at 500 keV is sufficiently space-charge dominated (space charge has ≈10-20 times the effect on the beam envelope compared with emittance) that standard 3 gradient or variable quad/profile methods are not accurate. Thus, a variation of the slit/slit sampling device will be used (5). A 0.1 mm wide vertically oriented, movable, water cooled slit will sample the beam. Approximately 2%-3% of the beam is transmitted. A wire scanner located 55 cm downstream of the slit will measure the width of the sampled beamlet. Taking data with the slit positioned at various points across the beam allows the transverse emittance to be determined. The wire scanner will be stepped to position in the beamlet where it will stop and collect the beam charge. A gated integrator will be used to measure the wire signal. Afterwards it will move to a new position, eventually tracing the beamlet profile. The energy and energy spread of each beamlet can be measured by turning on the spectrometer. Emittance as a function of radial distribution, bunch length, and bunch charge of the initial electrons will be made. Measurements of emittance are planned from bunch charges from 1 pC to 1 nC.

Bunch Length and Longitudinal Emittance

When the transverse emittance measurements are completed, a 1.497 GHz rectangular cavity will be installed in the beam line 48 cm downstream of the light box. The cavity will be driven in the TM120 mode giving a time varying kick to the beam as it passes through the cavity. If the bunch center reaches the center of the cavity at a zero crossing, it will receive no net kick. The head and tail, however will be kicked in opposite directions vertically. By using a wire scanner to measure the transverse profile downstream of the cavity, the bunch length can be extracted. Furthermore, if this beam is sent through a spectrometer, both energy and time information can be determined, thus providing information on the longitudinal emittance. There are problems associated with this measurement. These are: 1)the full beam diameter in the 500 keV region ranges from ≈10-20 mm; the kicker will give a ±5 mm vertical offset to the head and tail; this does not give sufficient resolution, 2)space charge will cause expansion of the beam in addition to the kicker cavity, causing error in the measurement, 3)off-axis fields in the kicker cavity will impart energy shear in particles vertically offset in the cavity (6); if the full beam passes through the cavity, the energy spread induced by this effect is on the order of the energy spread in the beam, thus resulting in error in the longitudinal emittance measurements, and 4) it is desirable to measure both bunch length and longitudinal emittance as a function of beam radius. These problems are alleviated by placing a round sampling aperture just prior to the kicker cavity. A 1 mm diameter aperture will cause the energy spread induced by the cavity to be < 10% of the nominal energy spread. In addition, a corrector dipole upstream of the aperture can be used to sweep the beam transversely, thus allowing different parts of the beam to pass through for subsequent measurement. The estimated transmission of the aperture is approximately 2%-3%. The planned measurements parallel those for the transverse emittance. As for the transverse emittance, the data will be analyzed and compared to PARMELA simulations.

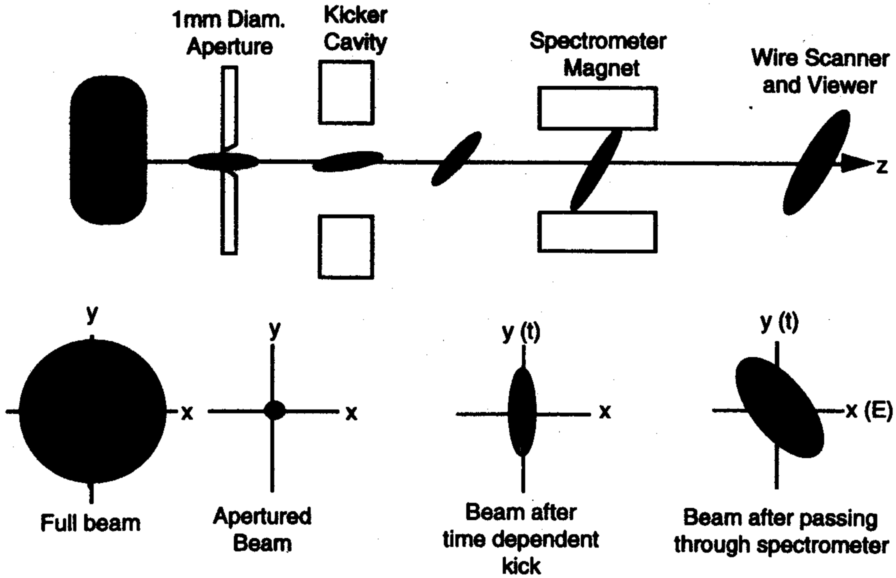
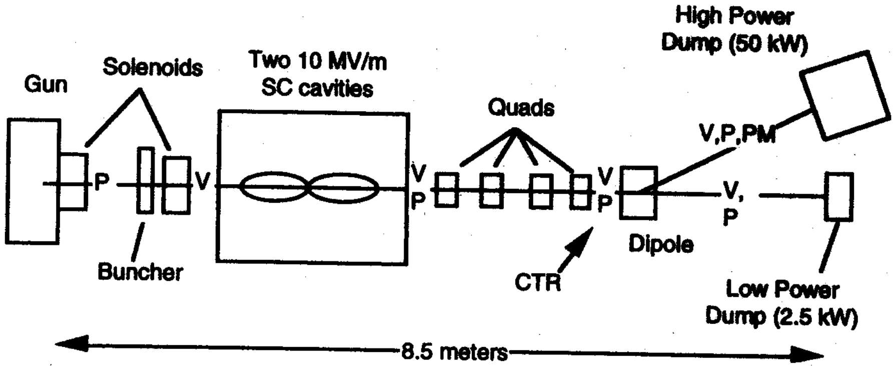


FIGURE 2. Progression of beam during measurement of longitudinal emittance and bunch length using a kicker cavity and spectrometer.

10 MEV INJECTOR TEST STAND

Upon completion of the 500 keV gun tests, the cryounit and 10 MeV beamline will be installed and 10 MeV tests will commence. A layout of the injector test stand configuration is shown in Figure 3. A buncher cavity and extra solenoid have replaced the apertures, kicker cavity, and spectrometer magnet that were installed for the gun tests. Following the 500 keV line are two 5-cell 1497 MHz superconducting cavities that will operate at 10 MV/m accelerating gradient, producing the final injector beam energy of 10 MeV. Following the cavities are 4 quadrupoles that will be used for emittance measurements and to match the beam during later injector experiments. OTR beam viewers immediately after the superconducting cavities and just prior to the spectrometer magnet will be used to thread the beam and to verify that the beam envelope is parallel emerging from the superconducting cavities. After the four quadrupoles is a spectrometer magnet followed by both a spectrometer leg and a straight-through section. The goals of the 10 MeV tests are to achieve nominal conditions while operating in a low power pulsed mode (100 nA average current) and to investigate long term operation at full power (5 mA average current). Nominal beam parameters to be measured are shown in Table 2 along with the corresponding diagnostic method and expected uncertainties. Each is discussed in following sections.



V = Viewer, flourescent at 500 keV, OTR at 10 MeV

PM = Stripline beam position monitor

P = profile diagnostic, wire scanner at 500 keV, OTR at 10 MeV

CTR = Coherent Transition Radiation Bunch length diagnostic

FIGURE 3. Layout of the 10 MeV beamline

Beam Position, Profile, Energy, Energy Spread, and Current

For most of the 10 MeV test stand experiments, beam position will be monitored using optical transition radiation (7) screens viewed using integrating CID cameras. These will also be used to center the beam in quadrupoles. The estimated resolution is 50 μm. Beam profiles will also be measured using the optical transition radiation (OTR) viewers. At locations after the spectrometer magnet, wire scanners will be used to verify the proper operation of the OTR profiling system. The viewers will be mounted on a plunger such that, when the viewer is extracted, a section of beampipe will be inserted so the impedance of the device is reduced (8).

The beam energy and energy spread will be set using the spectrometer viewer. During high power beam operation, a stripline BPM (9) developed at RHIC will be used to monitor energy stability. Design of the spectrometer leg is in process. The requirement for energy stability is 0.2% rms. For a horizontal dispersion of 50 cm, this energy jitter would produce beam motion of 0.5 mm. The nominal energy spread of 2% (4σ) would cause the beam to spread by 1 cm. The challenging aspect to the spectrometer region is the design of the beam dump.

Electrons of 10 MeV energy do not have penetrating power (few mm in copper). Thus, the full 50 kW of beam power will be deposited in a thin layer of copper. To avoid melting the copper, the beam will be strongly defocused by two quads from ≈0.8 cm diameter to ≈8 cm diameter. The beam will also be rastered to effectively expand the beam area to 200 cm^2. Unfortunately, the available space is only about 1.5 - 2 m . In this space, the beam must reach a high dispersion point and then be expanded. The spectrometer optics are currently under design.

TABLE 2. Summary of 10 MeV Beam Parameters and Associated Diagnostics

Parameter	Nominal value	Range	Technique	Anticipated Resolution
Position	0 mm	±5 mm	OTR viewers, BPMs	±0.25 mm
Profile	3 mm, rms	1-5 mm, rms	wire scanners, OTR viewers	50 μm
Energy	10 MeV	5 - 12 MeV	Spectrometer / viewer/BPM	0.1 MeV
Energy spread	0.2 MeV	0.05-0.3 MeV	Spectrometer wire scanner	0.01 MeV
Trans. emittance	5π mm-mrad, rms, normalized	TBD	Quad/profile	TBD
Bunch length	8 psec (4σ)	1-10 psec	Coherent Transition Radiation	0.25 psec
M56, time of arrival	0	±50 cm,	Phase detector and BPM pickup	≈1 mm, 0.1 psec
Long. emittance	11 keV-degrees	TBD	Slit, phase detector, CTR	TBD

Transverse Emittance Measurements

As in the 500 keV test stand, the nominal beam setup produces dynamics dominated by space charge. However, by focusing the beam sufficiently, emittance effects will begin to dominate. The standard techniques of measuring the beam envelope as a function of quadrupole can then be applied. For an estimate of the radius at which this will happen, the ratio of space charge defocusing to emittance defocusing on the beam envelope can be derived from the K-V envelope equation (10) and is given by

$$\frac{I\sigma_x^2}{2I_o\beta\gamma\varepsilon_{rms,N}^2} \qquad (1)$$

Here, I is the peak microbunch current, σ_x is the rms radius, I_o=1.7 × 10^4 A for electrons, β = relative velocity, γ is the relativistic energy factor, and $\varepsilon_{rms,N}$ is the rms, normalized emittance. At the exit of the cryounit where $\beta\gamma$ = 20.5, PARMELA simulation predicts that σ_x = 1.17 mm, I = 28 A, and $\varepsilon_{rms,N}$ = 4 π mm-mrad. For these values, the ratio is ≈3.9. The ratio becomes 0.5 for σ_x = 0.4 mm. PARMELA simulations predict that focusing the beam down to this radius does not degrade the emittance. In view of the small spot sizes, resolution of the profile monitor is an issue in the accuracy of the diagnostic. At the point where the profiles are to be measured, both wire scanner and OTR foils will be employed. The resolution of the wire scanner is 25 μm (11). Further simulations are underway to verify the accuracy of this method. Even if space charge can not be made negligible, space charge effects can be estimated and compensated for in the emittance calculations (12). Though this technique will most likely be employed to some extent, alternative methods to measure emittance are also under investigation including use of a high energy pepper pot (13) and optical transition radiation interferometry (14). Ideally, two emittance diagnostics will be in place so that cross-checks of the measurements can be done.

Bunch Length

Measurement of bunch length will be done using Coherent Transition Radiation (CTR). Transition radiation (15) is generated when a charged particle beam passes between regions of different dielectric constants. For short bunches, the transition radiation from different particles adds coherently causing the intensity of the radiation to be proportional to the square of the number of particles N, in contrast to incoherent radiation which is proportional to N. For picosecond and smaller bunch lengths, the coherent radiation is in the infrared. By measuring the autocorrelation of the coherent radiation, the bunch length and profile can be extracted (16, 17). A schematic of this device shown in Figure 4. A Michelson interferometer can be used to measure the autocorrelation of transition radiation emitted from a foil placed in the beamline. The device has been designed and two will be under construction in the near future. One device will be tested on the 45 MeV CEBAF injector prior to installation in the 10 MeV injector test stand. The estimated resolution is 0.1 psec over a range of 0.25 - 10 psec. To avoid absorption by water vapor, the device will be enclosed and purged with dry nitrogen. The diagnostic will be automated so that a measurement of bunch length and longitudinal profile will be extracted in less than 1 minute.

Later injector setups will use coherent synchrotron radiation to monitor the bunch length when operating at high power. The device currently under design can be used to measure synchrotron radiation as well as transition radiation.

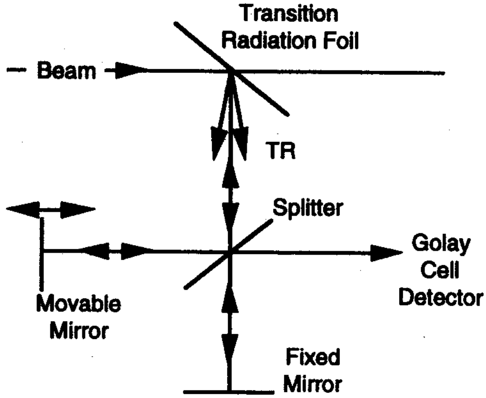


FIGURE 4. Schematic of CTR interferometer

Time of Arrival, M56, and Longitudinal Emittance

For later experiments involving bending the 10 MeV beam, it will be necessary to set the M_{56} transfer matrix term to zero. The value of M_{56} will be measured using the technique currently used at CEBAF (18). In this technique, a fundamental frequency pickup cavity detects the passage of the beam and a precision phase detector is used to measure time of arrival referenced to an external source. If $M_{56} = 0$, changes in energy will not affect the time of arrival at the pickup cavity. In order to save space and minimize impedance, the 10 MeV injector will employ a BPM instead of a cavity. However, care must be taken to make sure that the beam is centered in the BPM to obtain accurate data. A technique for measuring arrival time as a function of energy is currently under investigation. A slit is placed at a high dispersion point so that a specific energy range is allowed to pass. The time of arrival diagnostic discussed above will be placed immediately after the slit. This will give a measure of time versus energy. Furthermore, if a CTR bunch length device is then used to measure the longitudinal profile of the selected energy, all necessary information to calculate the longitudinal emittance will be available.

CONCLUSION

The diagnostics for the 500 keV gun test stand and the 10 MeV injector test stand for the CEBAF FEL injector are under development. The diagnostics will be used for the characterization of the gun and 10 MeV beamline and development of a reliable, experimentally verified PARMELA simulation model. Beam parameters to be measured include beam position, profile, energy, energy spread, transverse and longitudinal emittances, and M_{56}. Though several options are under investigation, the diagnostic technique to measure transverse emittance at 10 MeV is still undetermined.

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